



# *High Energy Muon Beams for HEP: R&D Towards World-Leading Intensity and Energy Frontier Physics Capabilities*

*BNL Frontier Capability Workshop*



Mark Palmer  
April 17, 2013



# The Aims of the Muon Accelerator Program



Muon accelerator R&D is focused on developing a facility that can address critical questions spanning two frontiers...

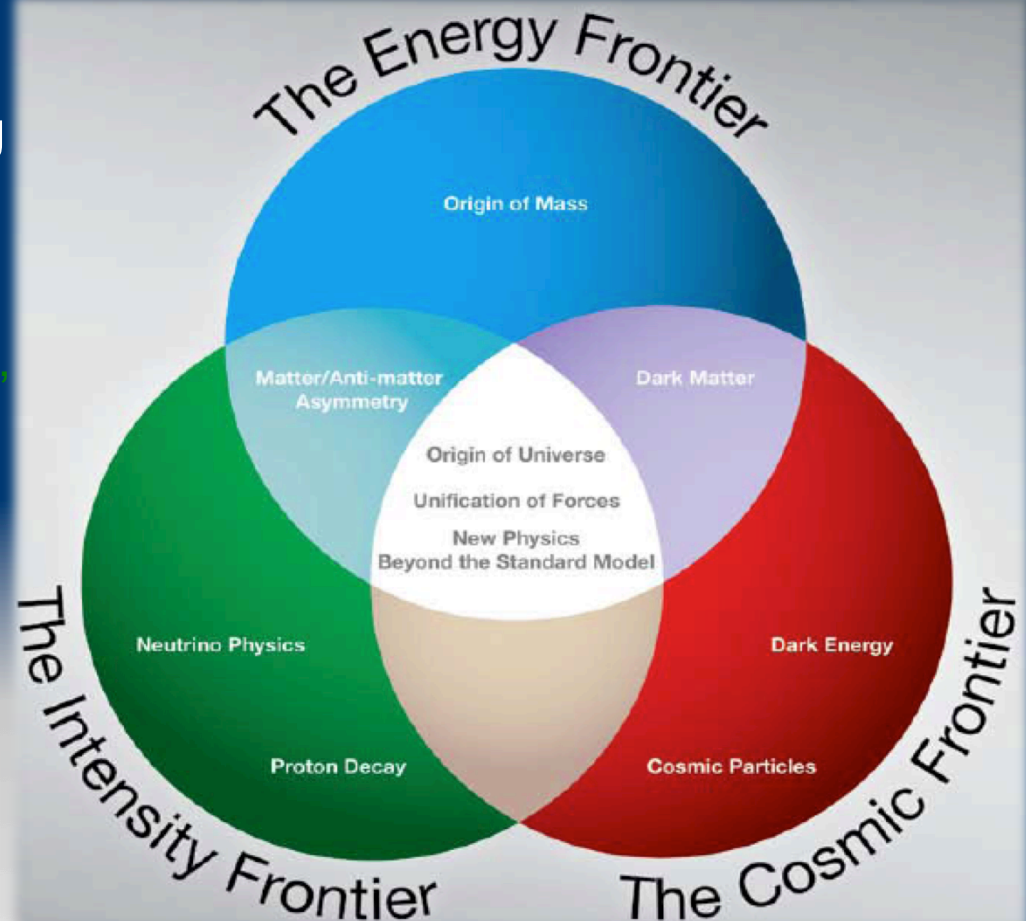
## The Intensity Frontier:

with a **Neutrino Factory** producing well-characterized  $\nu$  beams for precise, high sensitivity studies



## The Energy Frontier:

with a **Muon Collider** capable of reaching multi-TeV CoM energies  
and  
a **Higgs Factory** on the border between these Frontiers



**The unique potential of a facility based on muon accelerators is physics reach that SPANS 2 FRONTIERS**



# Outline

- Physics Motivations  $\Rightarrow$   
Neutrino Factories and Muon Colliders
- R&D Challenges
- Muon Accelerator Staging
  - Staging Scenarios
  - The Proposed Timeline
  - Parameters
- Concluding Remarks



# THE PHYSICS MOTIVATIONS

# The Physics Motivations



- $\mu$  – an elementary charged lepton:
  - 200 times heavier than the electron
  - 2.2  $\mu\text{s}$  lifetime at rest
- Physics potential for the HEP community using muon beams
  - Tests of Lepton Flavor Violation
  - Anomalous magnetic moment  $\Rightarrow$  hints of new physics (g-2)
  - Can provide equal fractions of electron and muon neutrinos at high intensity for studies of neutrino oscillations – the **Neutrino Factory** concept
  - Offers a large coupling to the “Higgs mechanism”
  - As with an  $e^+e^-$  collider, a  $\mu^+\mu^-$  **Collider** would offer a precision probe of fundamental interactions – in contrast to hadron colliders



$$\mu^+ \rightarrow e^+ \nu_e \bar{\nu}_\mu$$

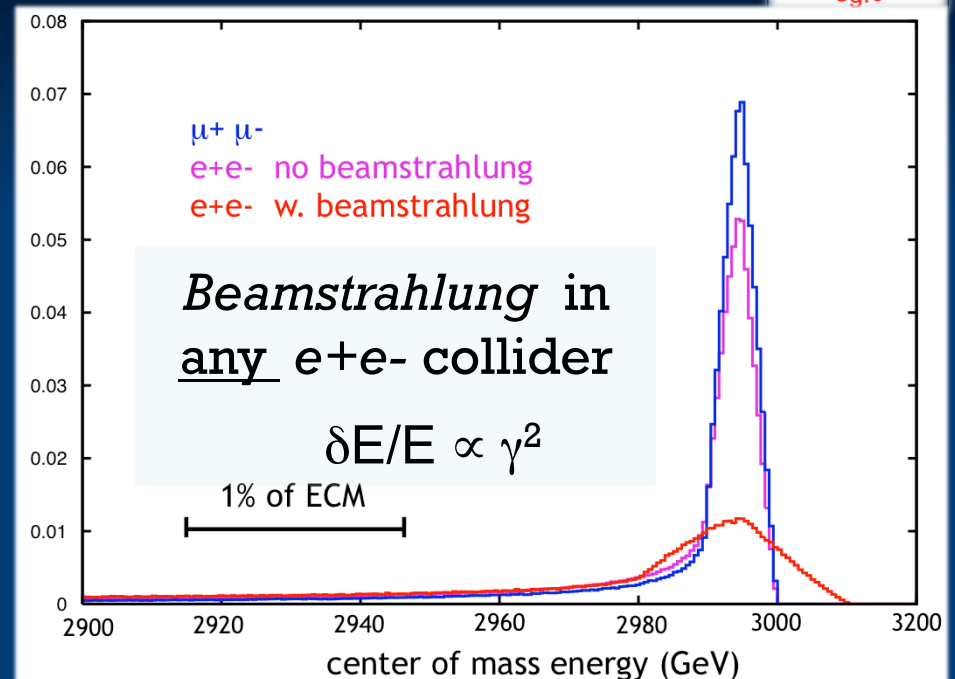
$$\mu^- \rightarrow e^- \bar{\nu}_e \nu_\mu$$

$$\sim \left( \frac{m_\mu^2}{m_e^2} \right) \cong 4 \times 10^4$$

# Muon Accelerator Physics



- Large muon mass strongly suppresses synchrotron radiation
  - ⇒ Muons can be accelerated and stored using rings at much higher energy than electrons
  - ⇒ Colliding beams can be of higher quality with reduced beamstrahlung



- Short muon lifetime has impacts as well
  - Acceleration and storage time of a muon beam is limited
  - Collider ⇒ a new class of decay backgrounds must be dealt with
- Precision beam energy measurement by g-2 allows precision Higgs width determination
- Muon beams produced as tertiary beams:
  - Offers key accelerator challenges...



# The Physics Needs: Neutrinos (I)

- In the neutrino sector it is critical to understand:

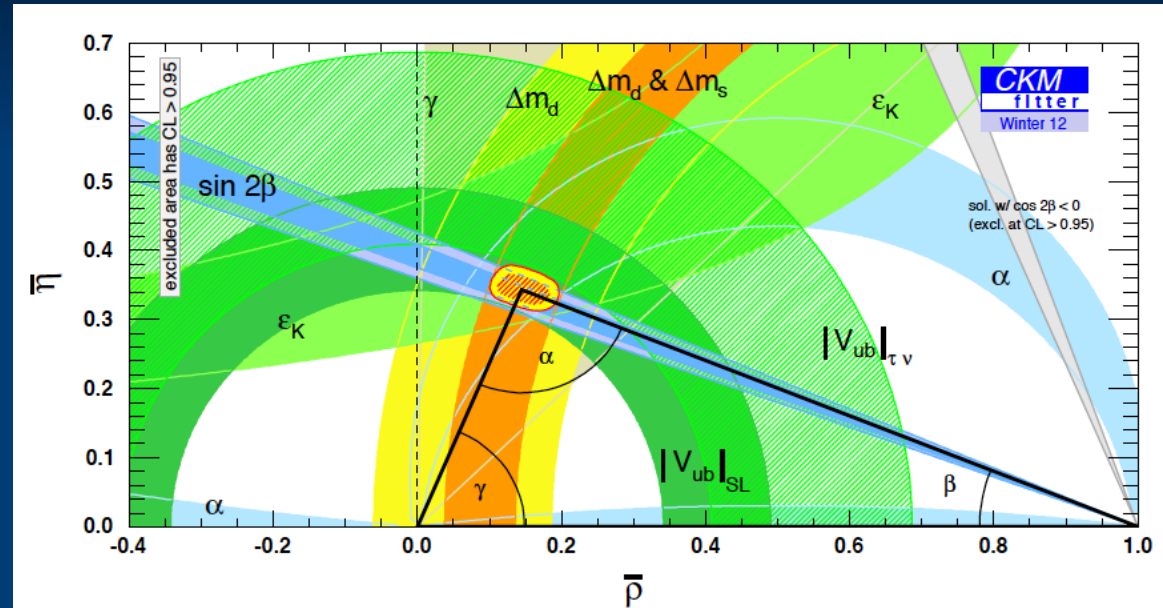
- $\delta_{CP}$

- The mass hierarchy

- $\theta_{23} = \pi/4$ ,  $\theta_{23} < \pi/4$   
or  $\theta_{23} > \pi/4$

- Resolve the LSND and other short baseline experimental anomalies [perhaps using beams from a muon storage ring ( **$\nu$ STORM**) in a short baseline experiment]

- And continue to probe for signs new physics



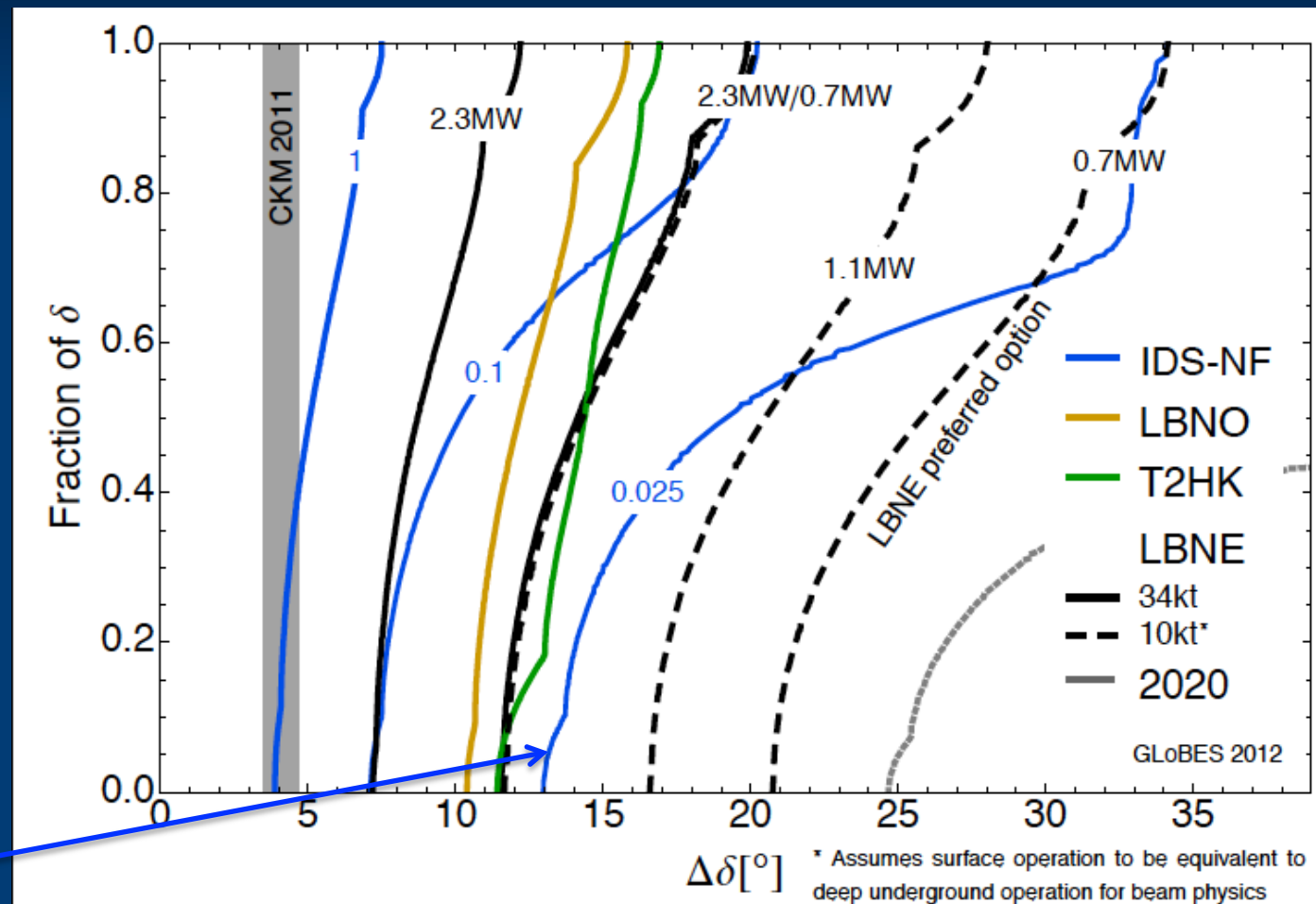
P. Huber

# The Physics Needs: Neutrinos (II)

- CP violation physics reach of various facilities

Can we probe the CP violation in the neutrino sector at the same level as in the CKM Matrix?

0.025 IDS-NF:  
700kW target,  
no cooling,  
 $2 \times 10^8$  s running time  
10-15 kTon detector



P. Coloma, P. Huber, J. Kopp, W. Winter – article in preparation

# The Physics Needs: Colliders

- $\mu^+\mu^-$  Collider:

- Center of Mass energy: 1.5 - 6 TeV (3 TeV)
- Luminosity  $> 10^{34} \text{ cm}^{-2} \text{ sec}^{-1}$  (350 fb $^{-1}$ /yr)
- Compact facility
  - 3 TeV - ring circumference 3.8 km
  - 2 Detectors
- Superb Energy Resolution

## Muon Collider Conceptual Layout

**Project X**  
Accelerate hydrogen ions to 8 GeV using SRF technology.

**Compressor Ring**  
Reduce size of beam.

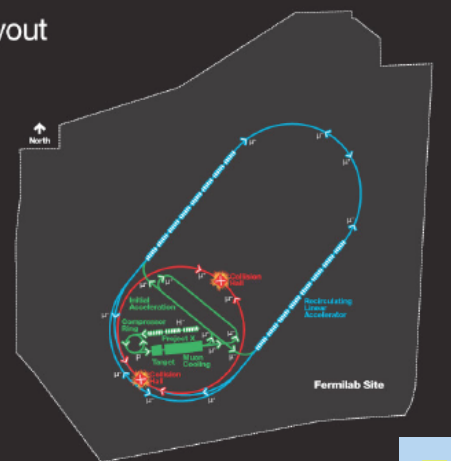
**Target**  
Collisions lead to muons with energy of about 200 MeV.

**Muon Capture and Cooling**  
Capture, bunch and cool muons to create a tight beam.

**Initial Acceleration**  
In a dozen turns, accelerate muons to 20 GeV.

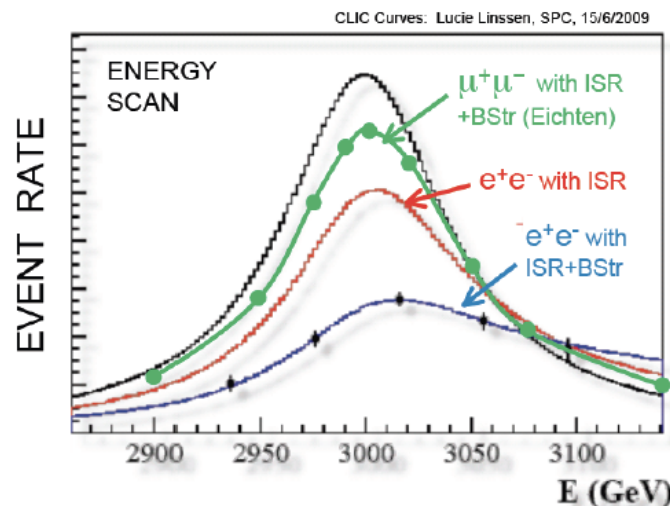
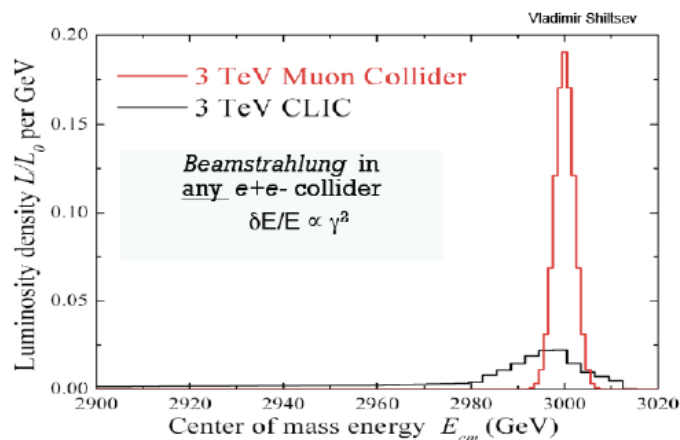
**Recirculating Linear Accelerator**  
In a number of turns, accelerate muons up to 3 TeV using SRF technology.

**Collider Ring**  
Bring positive and negative muons into collision at two locations 100 meters underground.



E. Eichten

- MC: 95% luminosity in  $dE/E \sim 0.1\%$
- CLIC: 35% luminosity in  $dE/E \sim 1\%$

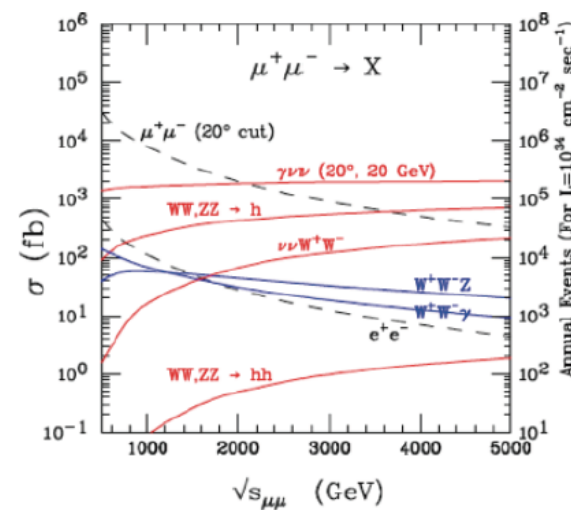
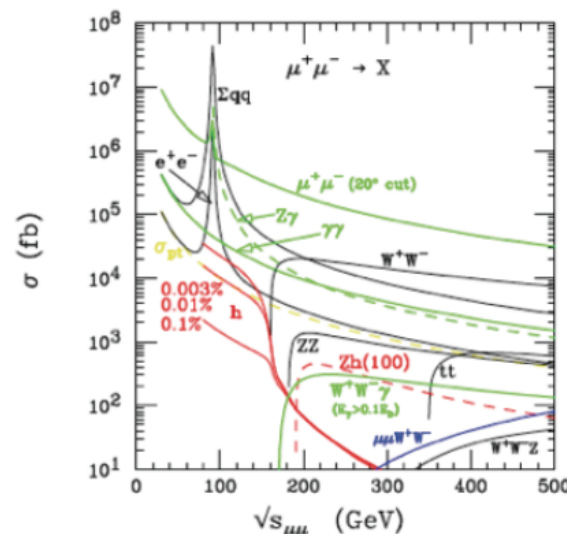
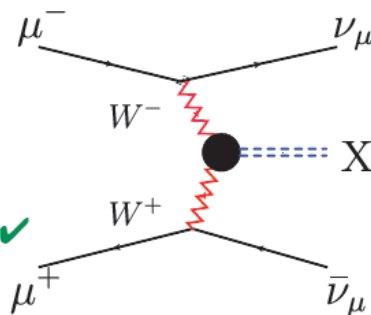


# Muon Collider Reach

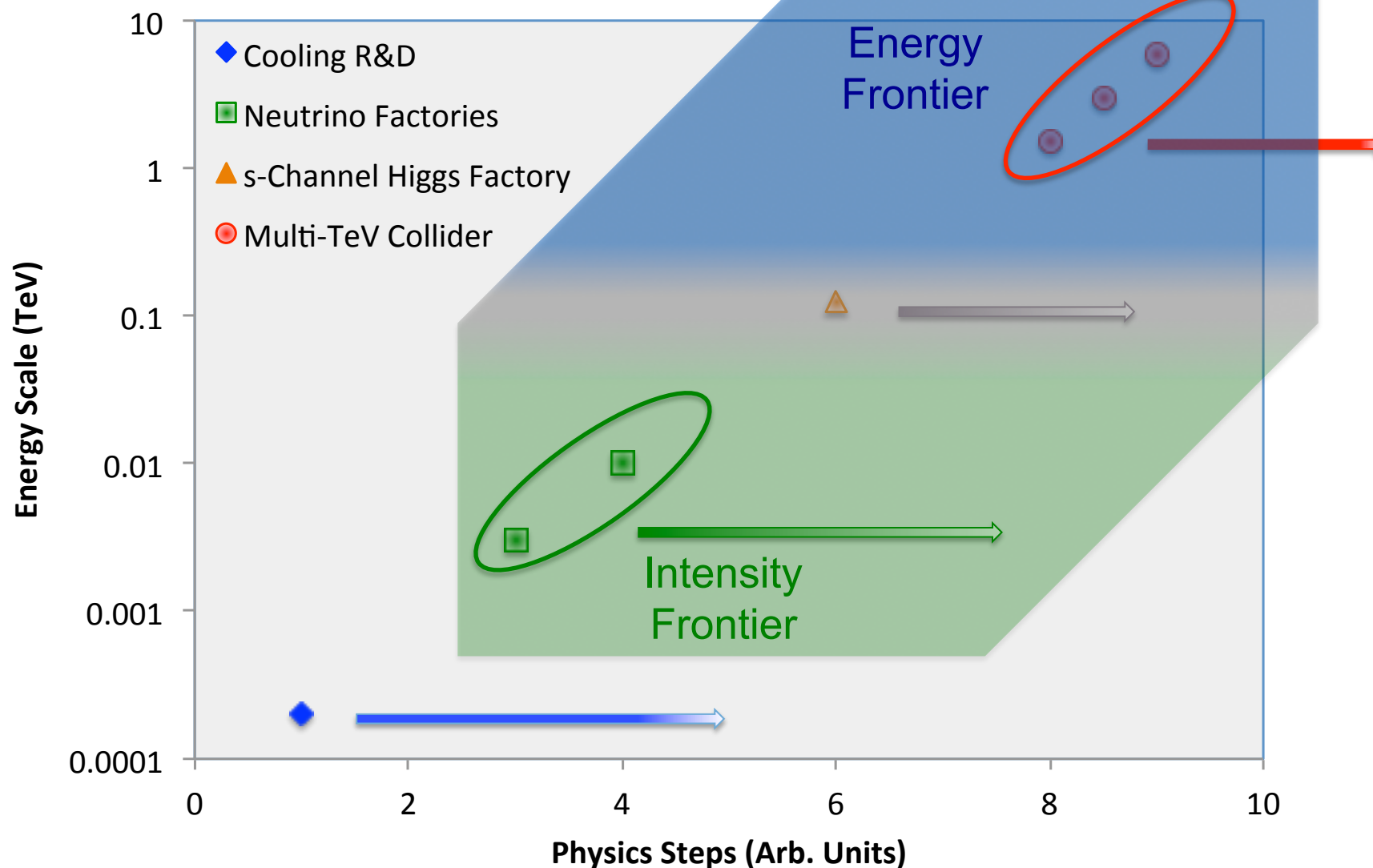
- For  $\sqrt{s} < 500$  GeV
  - SM thresholds:  $Z^0 h$ ,  $W^+ W^-$ , top pairs
  - Higgs factory ( $\sqrt{s} \approx 126$  GeV) ✓
- For  $\sqrt{s} > 500$  GeV
  - Sensitive to possible Beyond SM physics.
  - High luminosity required. ✓
    - Cross sections for central ( $|\theta| > 10^\circ$ ) pair production  $\sim R \times 86.8$  fb/s (in  $\text{TeV}^2$ ) ( $R \approx 1$ )
    - At  $\sqrt{s} = 3$  TeV for  $100 \text{ fb}^{-1} \sim 1000$  events/(unit of  $R$ )
- For  $\sqrt{s} > 1$  TeV
  - Fusion processes important at multi-TeV MC

$$\sigma(s) = C \ln\left(\frac{s}{M_X^2}\right) + \dots$$

- An Electroweak Boson Collider ✓



# Muon Accelerator Physics Scope



# Muon Accelerators



Accelerator	Energy Scale	Performance
<b>Cooling Channel</b>	<b>~200 MeV</b>	<b>Emittance Reduction</b>
<i>MICE</i>	<i>160-240 MeV</i>	<i>10%</i>
<b>Muon Storage Ring</b>	<b>3-4 GeV</b>	<b>Useable <math>\mu</math> decays/yr*</b>
<i><math>\nu</math>STORM</i>	<i>3.8 GeV</i>	<i><math>3 \times 10^{17}</math></i>
<b>Intensity Frontier <math>\nu</math> Factory</b>	<b>4-10 GeV</b>	<b>Useable <math>\mu</math> decays/yr*</b>
<i>FNAL NF Phase I (PX Ph 2)</i>	<i>4-6 GeV</i>	<i><math>9 \times 10^{19}</math></i>
<i>FNAL NF Phase II (PX Ph 2)</i>	<i>4-6 GeV</i>	<i><math>1 \times 10^{21}</math></i>
<i>IDS-NF Design</i>	<i>10 GeV</i>	<i><math>5 \times 10^{20}</math></i>
<b>Higgs Factory</b>	<b>~126 GeV CoM</b>	<b>Higgs/yr</b>
<i>s-Channel <math>\mu</math> Collider</i>	<i>~126 GeV CoM</i>	<i>5,000-40,000</i>
<b>Energy Frontier <math>\mu</math> Collider</b>	<b>&gt; 1 TeV CoM</b>	<b>Avg. Luminosity</b>
<i>Opt. 1</i>	<i>1.5 TeV CoM</i>	<i><math>1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>
<i>Opt. 2</i>	<i>3 TeV CoM</i>	<i><math>4.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>
<i>Opt. 3</i>	<i>6 TeV CoM</i>	<i><math>12 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>

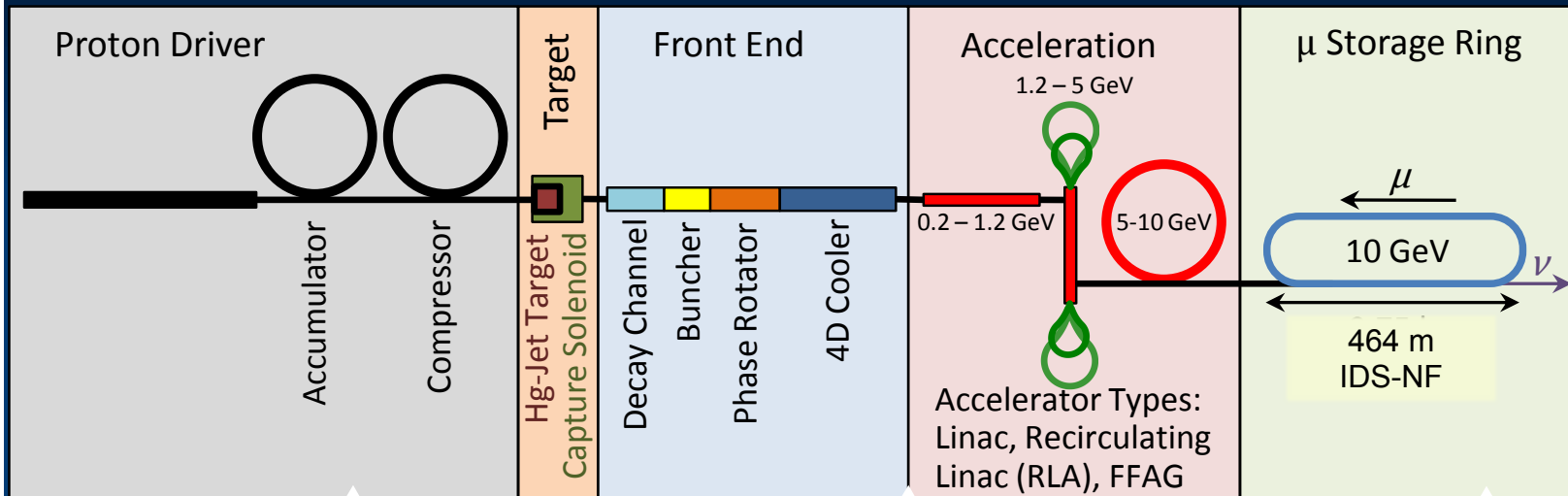
\* Decays of an individual species (ie,  $\mu^+$  or  $\mu^-$ )



Program Baselines

And Potential Staging Steps

# Neutrino Factory Concept



IDS-NF:  
4 MW Proton Source  
(eg, Project X Stage IV) with  
~2ns long bunches

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MAP  
Muon Accelerator Staging  
Study:  
Utilize Project X Stage II beam  
starting at 1MW

ν Factory Goal:  
 $O(10^{21})$  μ/year  
within the  
accelerator  
acceptance

IDS-NF:  
10 GeV Ring pointed at a  
magnetized detector @2500km

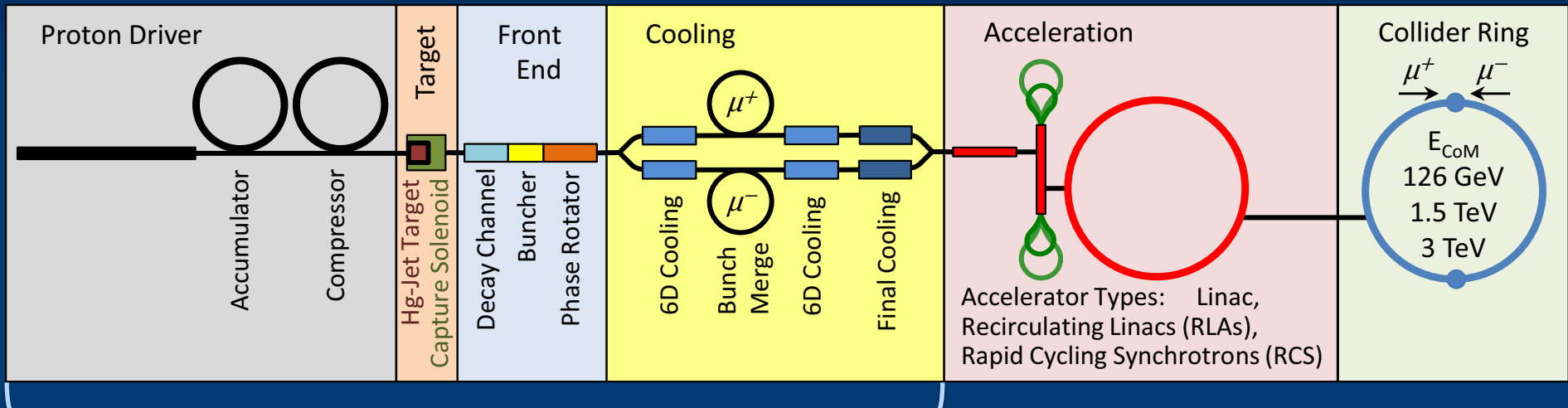
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MAP  
Muon Accelerator Staging Study:  
Studying a ~5GeV ring delivering  
νs to Homestake

# Muon Collider Concept



## Muon Collider Block Diagram



Proton source:  
For example PROJECT X  
Stage IV at 4 MW, with  
 $2 \pm 1$  ns long bunches

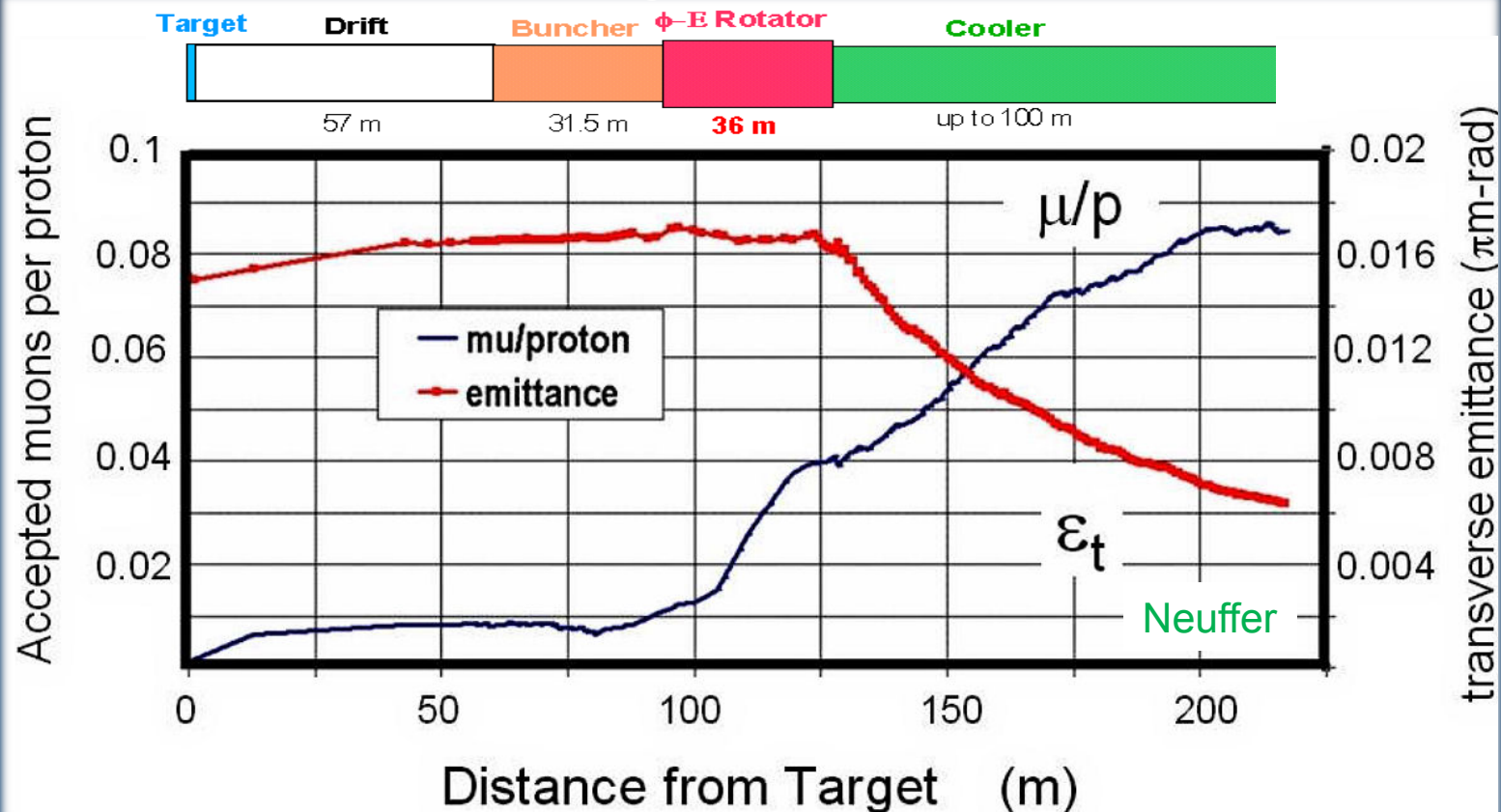
Goal:  
Produce a high intensity  
 $\mu$  beam whose 6D phase  
space is reduced by a  
factor of  $\sim 10^6$ - $10^7$  from its  
value at the production  
target

Collider:  $\sqrt{s} = 3$  TeV  
Circumference 4.5km  
 $L = 3 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$   
 $\mu/\text{bunch} = 2 \times 10^{12}$   
 $\sigma(p)/p = 0.1\%$   
 $\varepsilon_{\perp N} = 25 \text{ } \mu\text{m}$ ,  $\varepsilon_{\parallel N} = 72 \text{ mm}$   
 $\beta^* = 5 \text{ mm}$   
Rep. Rate = 12 Hz



# THE R&D CHALLENGES

# Technology Challenges – Tertiary Production

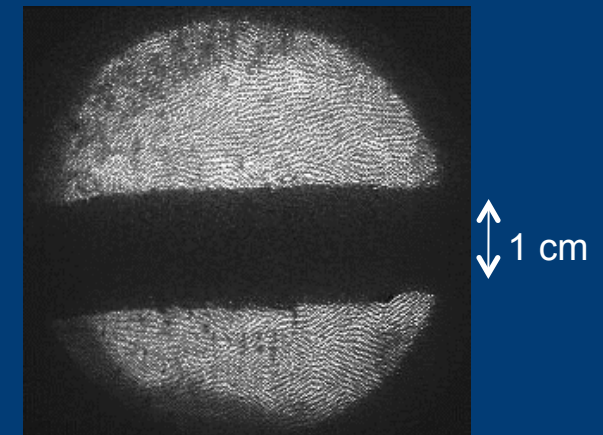
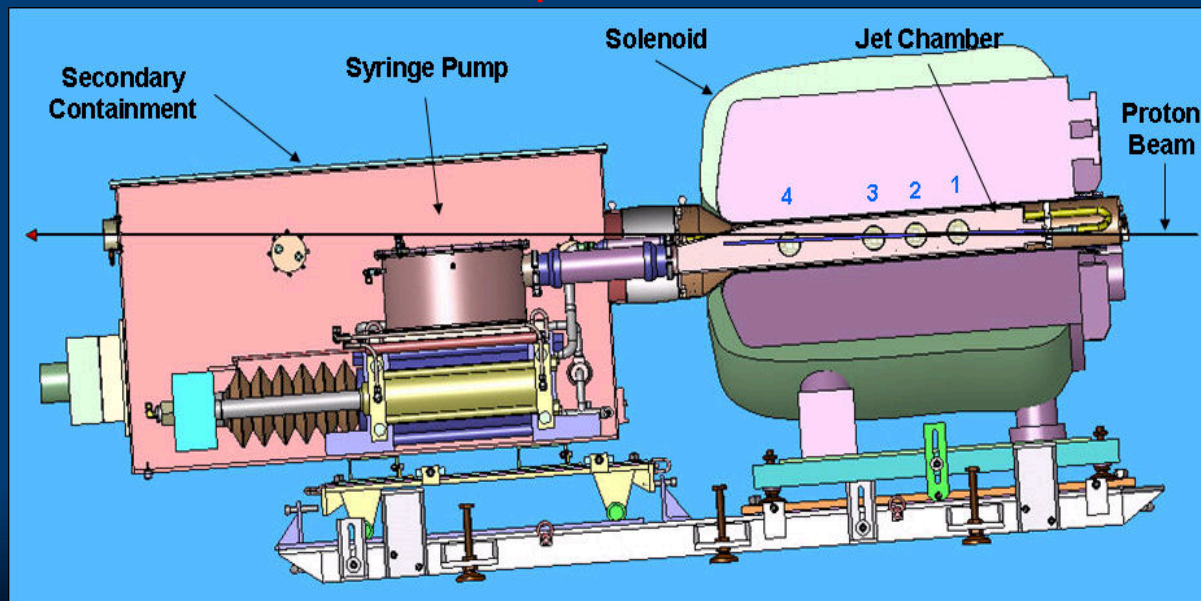
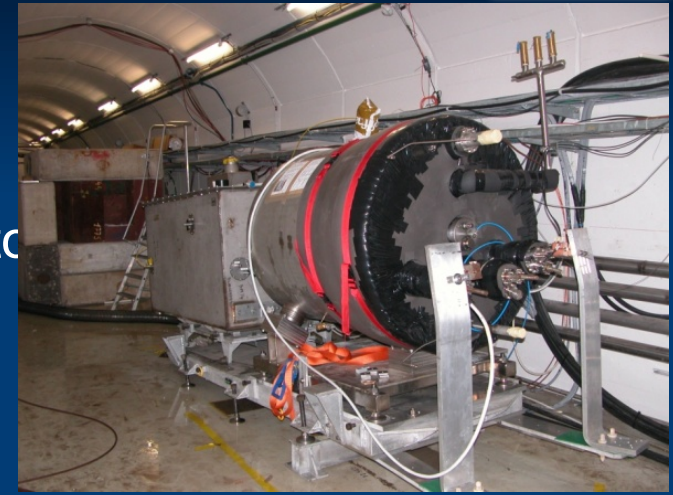


- A multi-MW proton source, e.g., Project X, will enable  $O(10^{21})$  muons/year to be produced, bunched and cooled to fit within the acceptance of an accelerator.

# Technology Challenges - Target



- The MERIT Experiment at the CERN PS
    - Proof-of-principle demonstration of a liquid Hg jet target in high-field solenoid in Fall '07
    - Demonstrated a 20m/s liquid Hg jet injected into a 15 T solenoid and hit with a 115 KJ/pulse beam!
- ⇒ Technology OK for beam powers up to 8 MW with a repetition rate of 70 Hz!



Hg jet in a 15 T solenoid with measured disruption length  $\sim 28$  cm

# Technology Challenges – Capture Solenoid

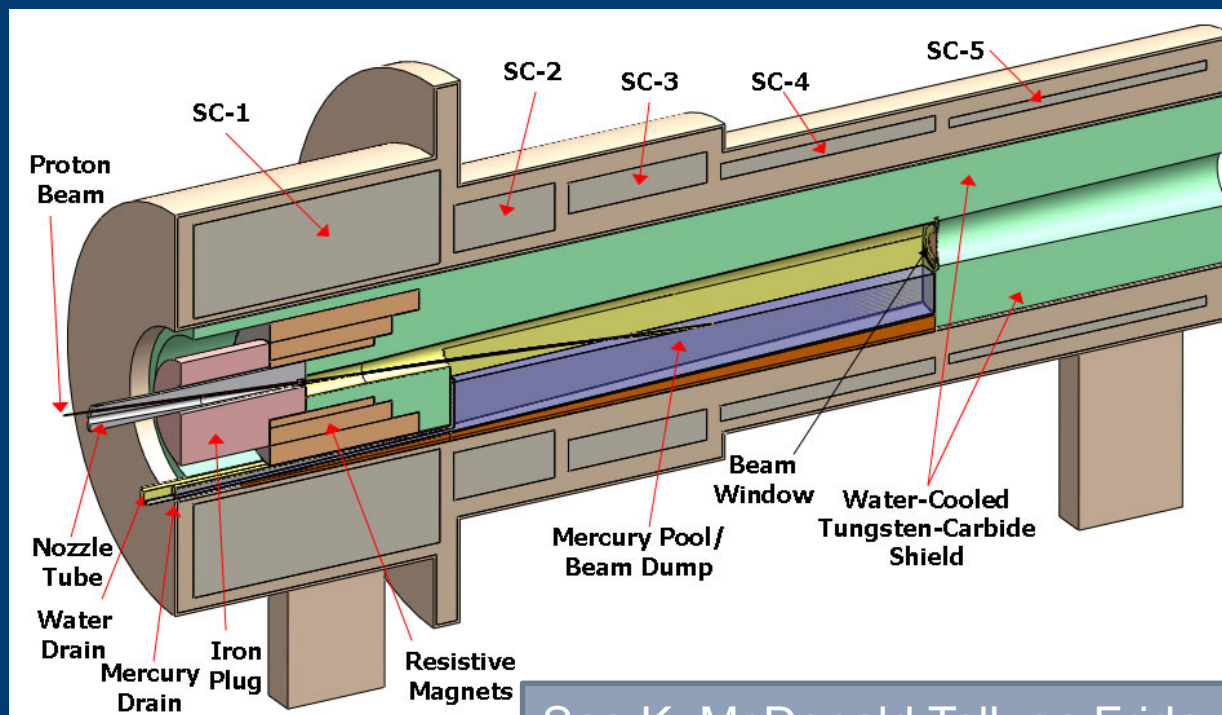


- A Neutrino Factory and/or Muon Collider Facility requires challenging magnet design in several areas:
  - Target Capture Solenoid (15-20T with large aperture)

$$E_{\text{stored}} \sim 3 \text{ GJ}$$

O(10MW) resistive coil in high radiation environment

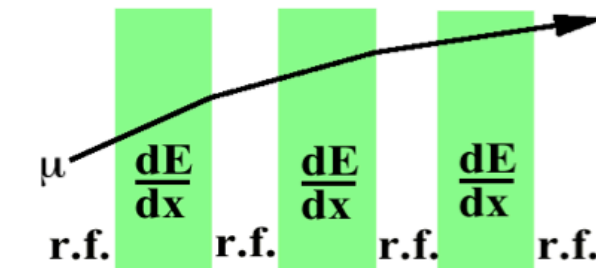
Possible application for High Temperature Superconducting magnet technology



See K. McDonald Talk on Friday

# Ionization Cooling

## • Muons cool via $dE/dx$ in low- $Z$ medium



– Absorbers:

$$\begin{cases} E \rightarrow E - \left\langle \frac{dE}{dx} \right\rangle \Delta s \\ \theta \rightarrow \theta + \theta_{space}^{rms} \end{cases}$$

ionization energy loss

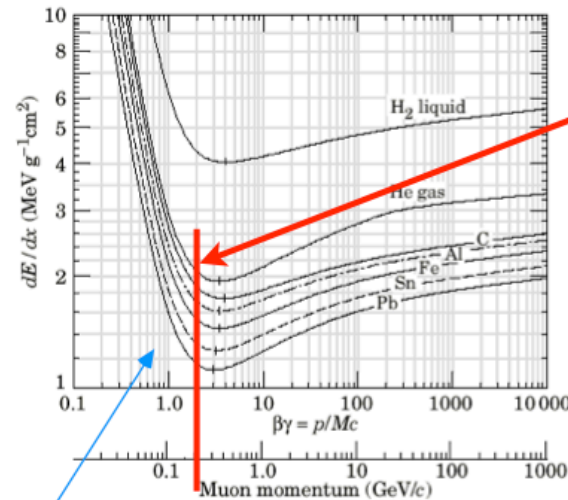
multiple Coulomb scattering

– RF cavities between absorbers replace  $\Delta E$

– Net effect: reduction in  $p_{\perp}$  at constant  $p_{\parallel}$ , i.e., transverse cooling

$$\frac{d\epsilon_N}{ds} \approx -\frac{1}{\beta^2} \left\langle \frac{dE_{\mu}}{ds} \right\rangle \frac{\epsilon_N}{E_{\mu}} + \frac{\beta_{\perp} (0.014 \text{ GeV})^2}{2\beta^3 E_{\mu} m_{\mu} X_0}$$

(emittance change per unit length)



• ionization minimum is  $\approx$  optimal working point:

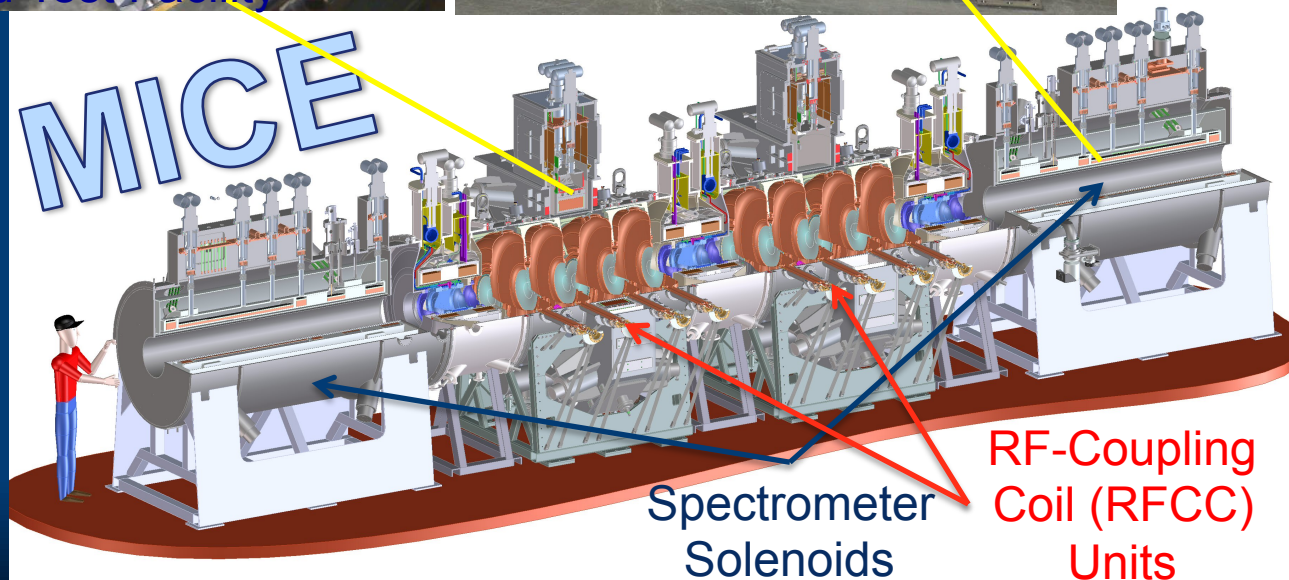
- ▶ longitudinal +ive feedback at lower  $p$
- ▶ straggling & expense of reacceleration at higher  $p$

• 2 competing effects  $\Rightarrow$   
 $\exists$  equilibrium emittance

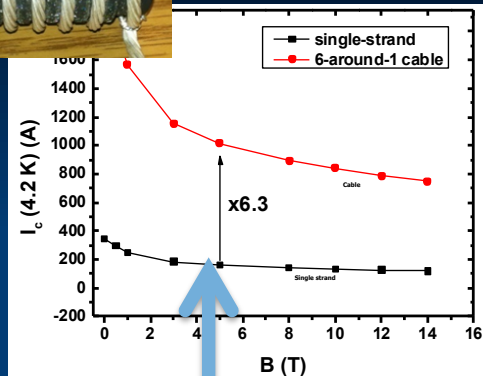
# Muon Ionization Cooling Experiment (MICE)



- Tertiary production of muon beams
  - Initial beam emittance intrinsically large
- Muon Cooling  $\Rightarrow$  Ionization Cooling
  - $dE/dx$  energy loss in materials
  - RF to replace  $p_{long}$

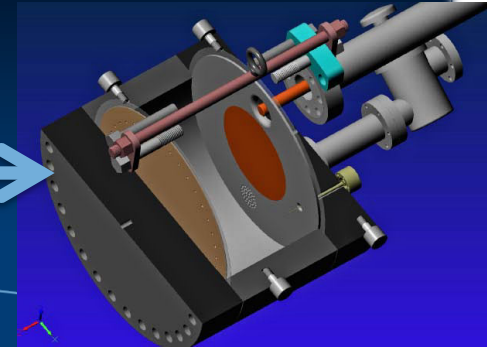


# Recent Technology Highlights



**Successful Operation of 805 MHz “All Seasons” Cavity in 3T Magnetic Field under Vacuum**

MuCool Test Area/Muons Inc



**Breakthrough in HTS Cable Performance with Cables Matching Strand Performance**

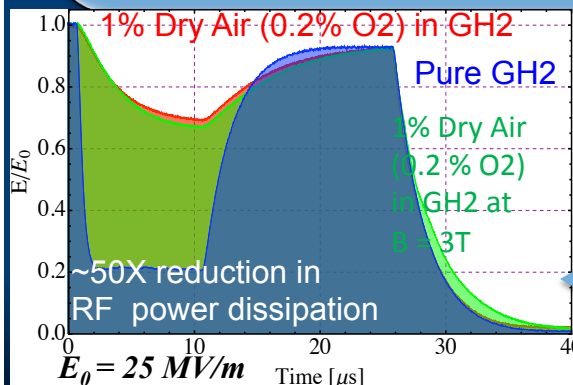
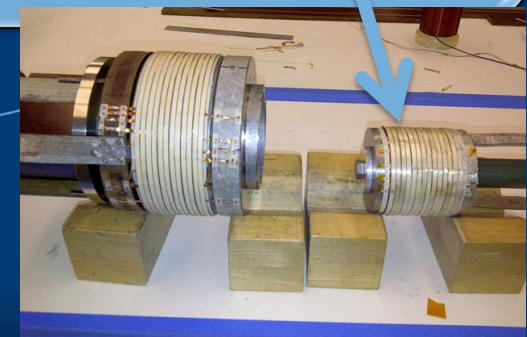
FNAL-Tech Div  
T. Shen-Early Career Award

**The Path to a Viable Muon Ionization Cooling Channel**

**World Record HTS-only Coil**

15T on-axis field  
16T on coil

PBL/BNL



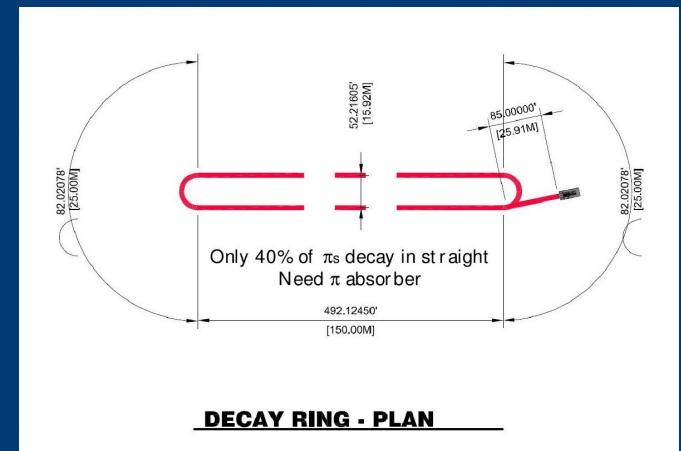
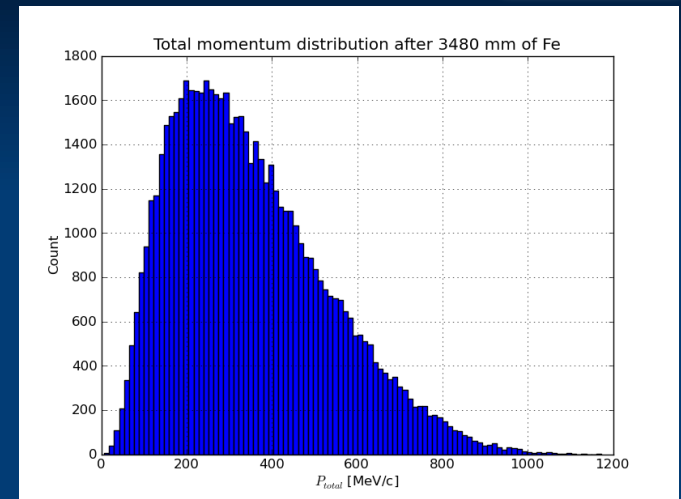
**Demonstration of High Pressure RF Cavity in 3T Magnetic Field with Beam**

Extrapolates to  
μ-Collider Parameters  
MuCool Test Area

# $\nu$ Storm as an R&D platform



- A high-intensity pulsed muon source
- $100 < p_\mu < 300$  MeV/c muons
  - Using extracted beam from ring
  - $10^{10}$  muons per 1  $\mu$ sec pulse
- Beam available simultaneously with physics operation
  - Sterile  $\nu$  search
  - $\nu$  cross section measurements needed for ultimate precision in long baseline measurements
- $\nu$ STORM also presents the opportunity to design, build and test decay ring instrumentation (BCT, momentum spectrometer, polarimeter) to measure and characterize the circulating muon flux.



More on this in a moment...

# MAP Feasibility Assessment Goals



Within the 6-year time frame:

- *To deliver results that will permit the high-energy physics community to make an informed choice of the optimal path to a high-energy lepton collider and/or a next-generation neutrino beam facility*

*As well as...*

- *To explore the path towards a facility that can provide cutting edge performance at both the Intensity Frontier and the Energy Frontier*
- *To validate the concepts that would enable the Fermilab accelerator complex to support these goals*

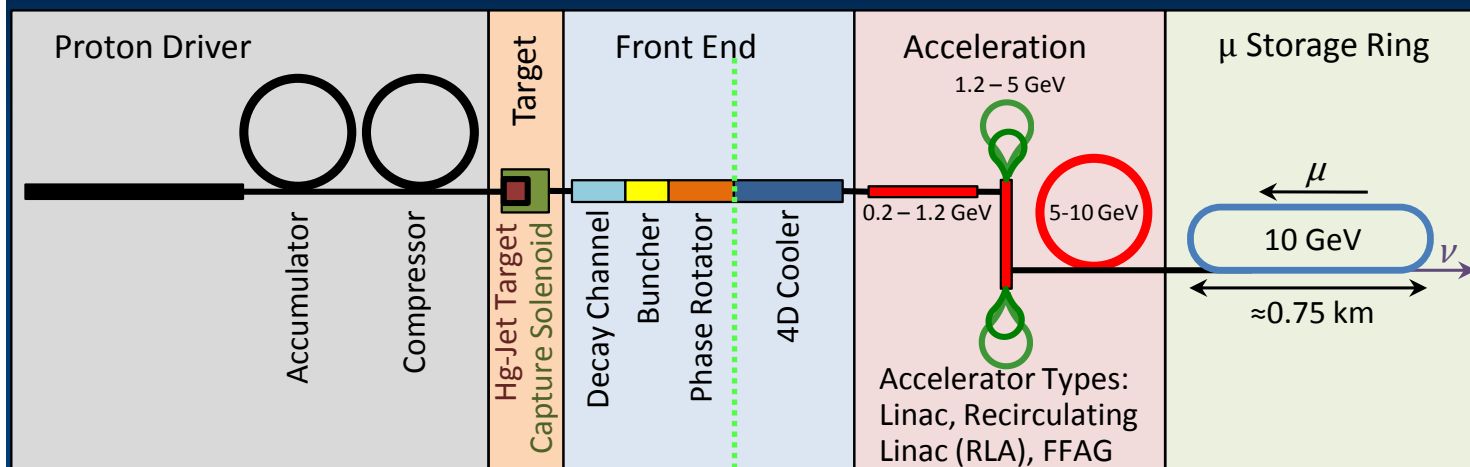


# MUON ACCELERATOR STAGING

MAP  $\Rightarrow$  Muon Accelerator Staging Study (MASS) Working Group  
J.P. Delahaye - chair

# Muon Collider - Neutrino Factory Comparison

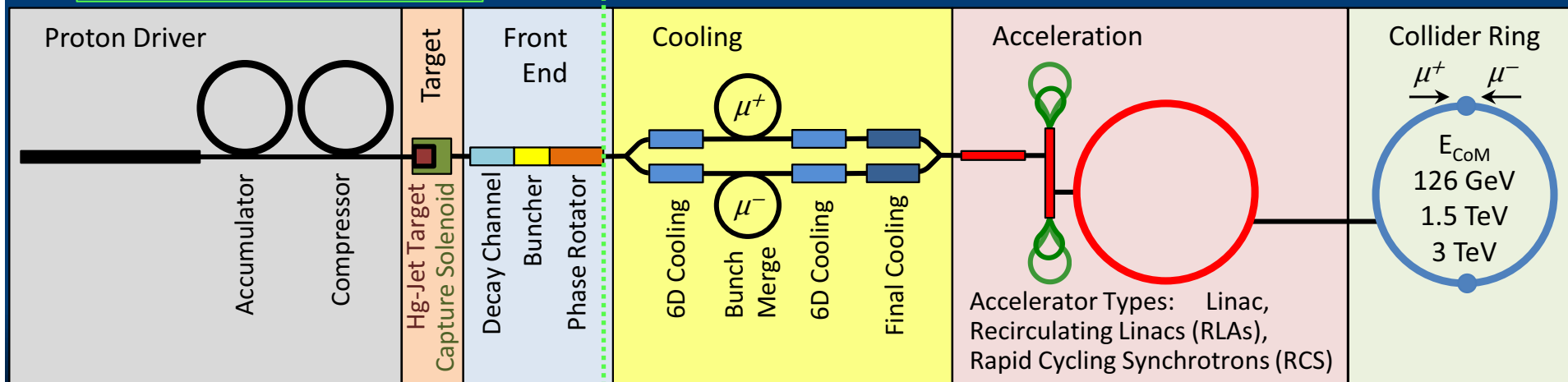
## NEUTRINO FACTORY



$\nu$  Factory Goal:  
 $O(10^{21})$   $\mu$ /year  
 within the  
 accelerator  
 acceptance

Share same complex

## MUON COLLIDER



# A Staged Muon-Based Neutrino and Collider Physics Program



The plan is conceived in four stages, whose exact order remains to be worked out:

- The “entry point” for the plan is the  $\nu$ STORM facility proposed at Fermilab, which can advance short-baseline physics by making definitive observations or exclusions of sterile neutrinos. Secondly, it can make key measurements to reduce systematic uncertainties in long-baseline neutrino experiments. Finally, it can serve as an R&D platform for demonstration of accelerator capabilities pre-requisite to the later stages.
- A stored-muon-beam Neutrino Factory can take advantage of the large value of  $\theta_{13}$  recently measured in reactor-antineutrino experiments to make definitive measurements of neutrino oscillations and their possible violation of CP symmetry.
- Thanks to suppression of radiative effects by the muon mass and the  $m_{\text{lepton}}^2$  proportionality of the  $s$ -channel Higgs coupling, a “Higgs Factory” Muon Collider can make uniquely precise measurements of the 126 GeV boson recently discovered at the LHC.
- An energy-frontier Muon Collider can perform unique measurements of Terascale physics, offering both precision and discovery reach.

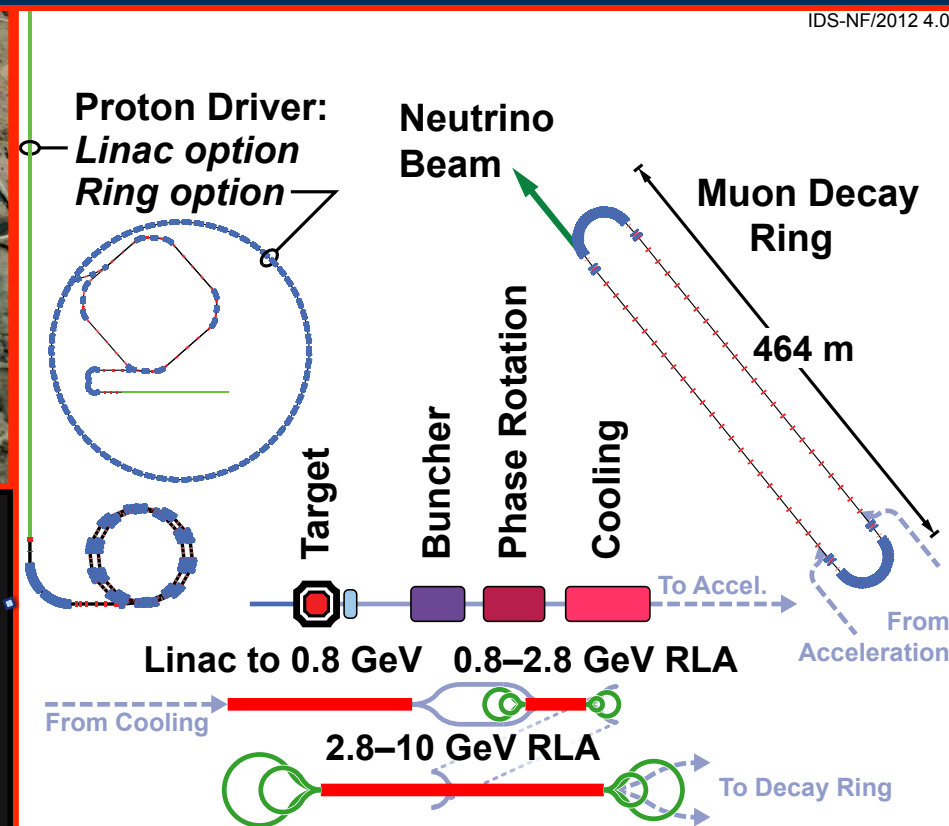
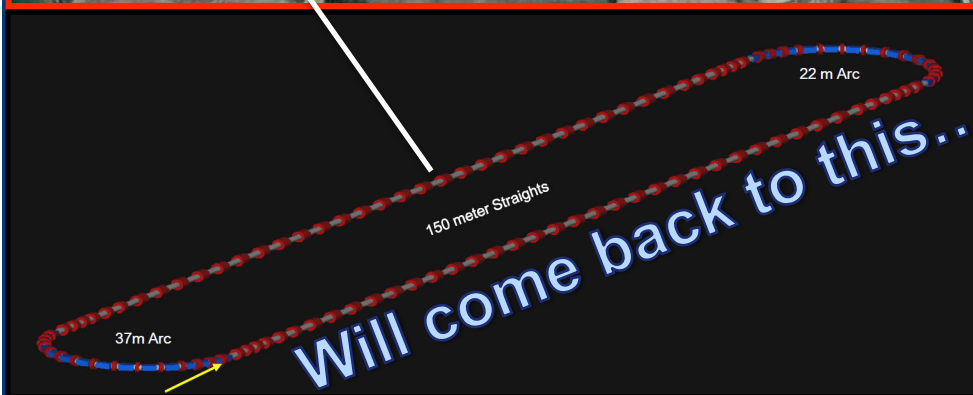
# All proposed muon-based accelerators would easily fit at Fermilab



$\nu$ STORM (entry level Neutrino Factory)

Intensity Frontier Neutrino Factory

IDS-NF/2012 4.0



$\nu$ STORM would provide important physics output and critical R&D leverage

Also a muon-based Higgs Factory or Energy Frontier Muon Collider

# How Could the Staged NF to Homestake Perform?



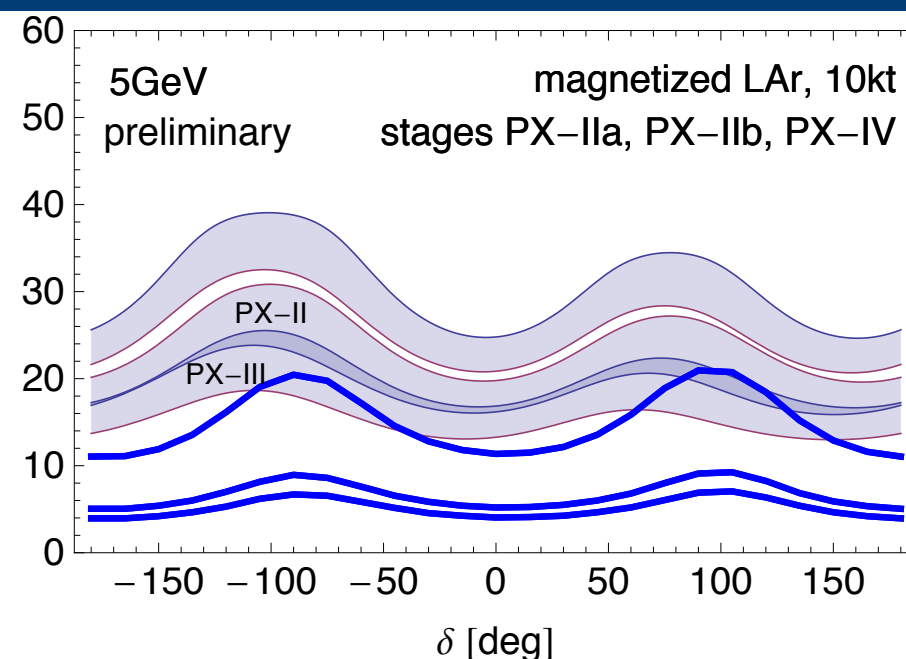
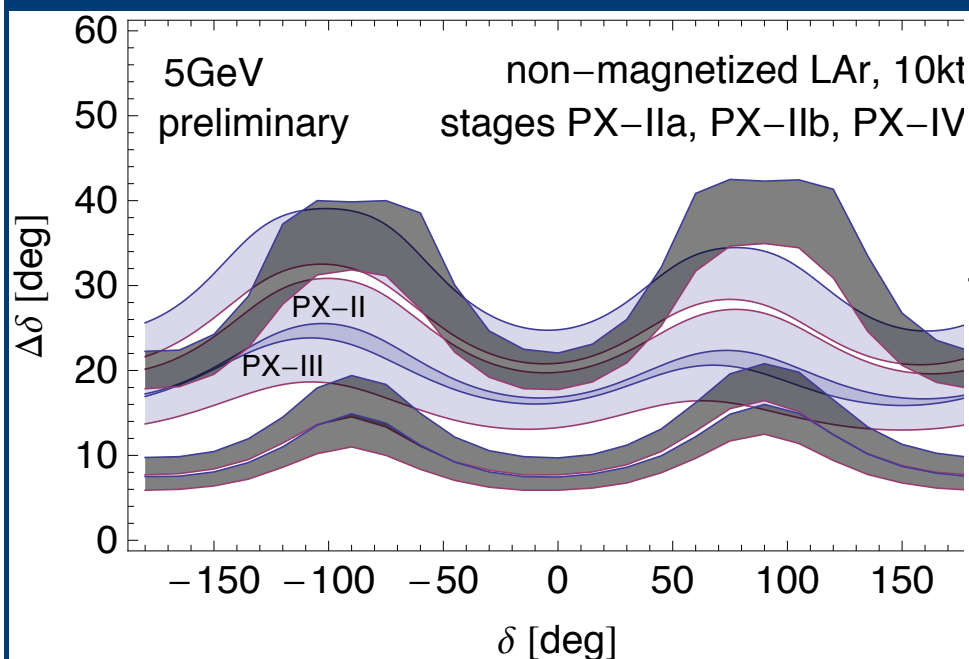
What if we send beam to LBNE?

1 MW, no muon cooling

⇒ 3 MW, w/cooling

⇒ 4 MW, w/cooling

What if we were able to have a magnetized LAr detector?

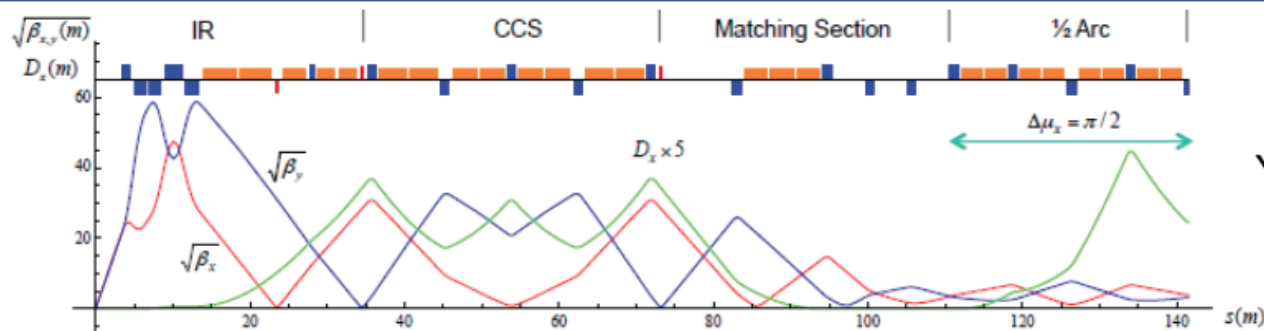


Gray bands represent range of possible detector performance per arXiv:0805.2019

Plots courtesy of P. Huber

Plots assume 100 kt-years

# Updated 63 x 63 GeV Lattice

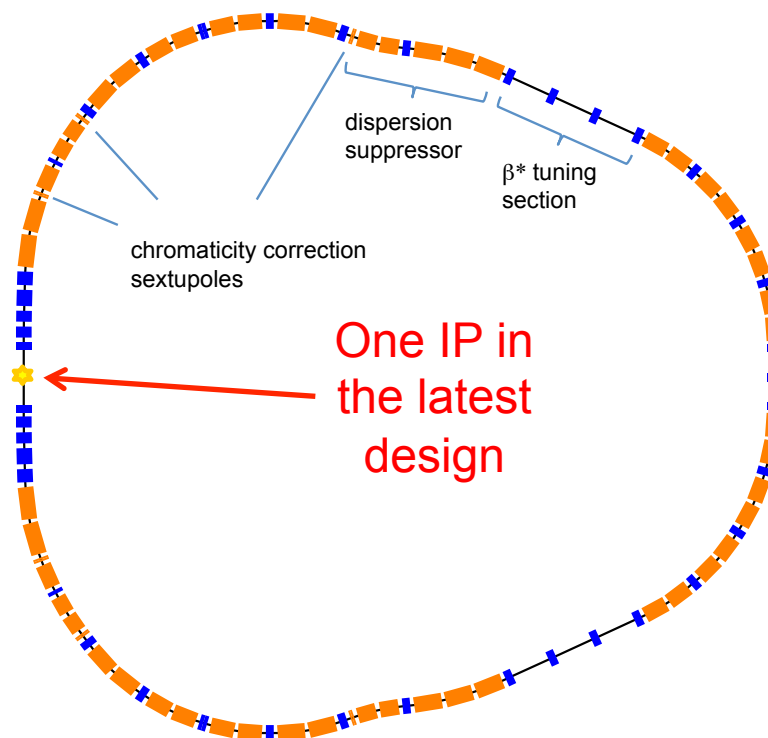


Y. Alexahin

Optics functions in half ring for  $\beta^* = 2.5 \text{ cm}$

## Parameter

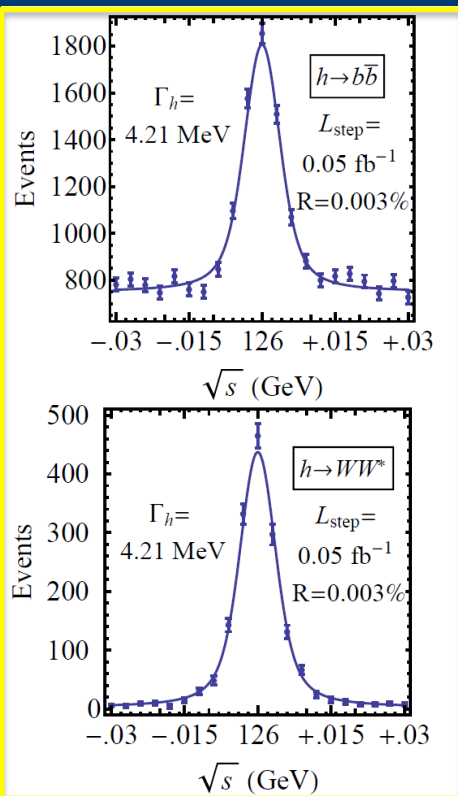
Beam energy	GeV	63	63
Average luminosity	$10^{31}/\text{cm}^2/\text{s}$	1.7	8.0
Collision energy spread	MeV	3	4
Circumference, C	m	300	300
Number of IPs	-	1	1
$\beta^*$	cm	3.3	1.7
Number of muons / bunch	$10^{12}$	2	4
Number of bunches / beam	-	1	1
Beam energy spread	%	0.003	0.004
Normalized emittance, $\epsilon_{\perp N}$	$\pi\text{-mm-rad}$	0.4	0.2
Longitudinal emittance, $\epsilon_{\parallel N}$	$\pi\text{-mm}$	1.0	1.5
Bunch length, $\sigma_s$	cm	5.6	6.3
Beam size at IP, r.m.s.	mm	0.15	0.075
Beam size in IR quads, r.m.s.	cm	4	4
Beam-beam parameter	-	0.005	0.02
Repetition rate	Hz	30	15
Proton driver power	MW	4	4



# 126 GeV Higgs Factory

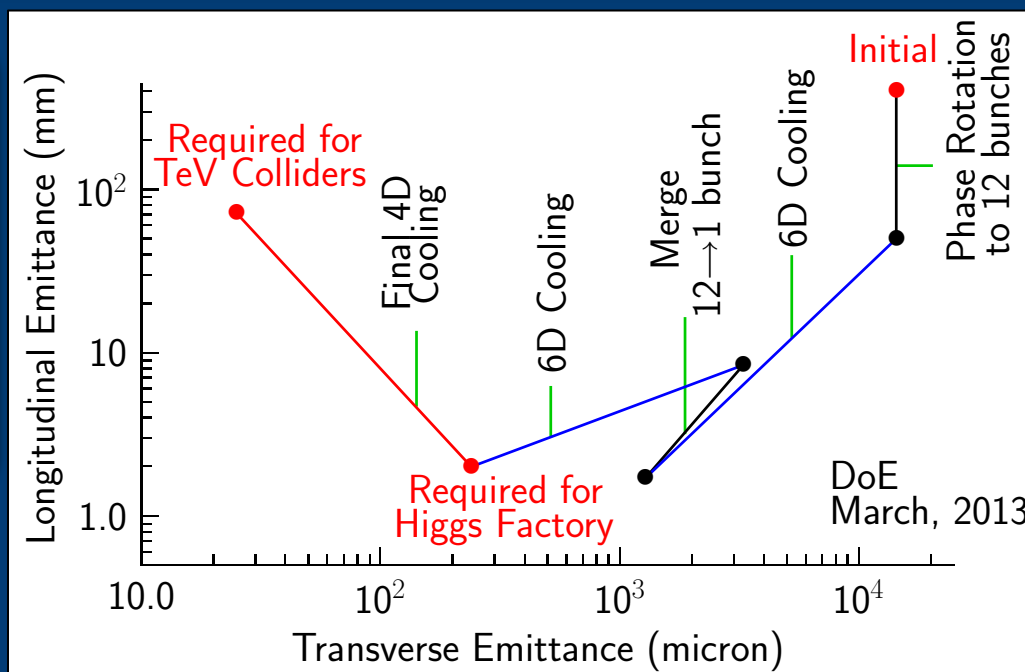


**s-channel coupling of Muons to HIGGS with high cross sections:**  
**Muon Collider of with  $L = 10^{32} \text{ cm}^{-2}\text{s}^{-1}$  @ 63 GeV/beam (50000 Higgs/year)**  
**Competitive with e+/e- Linear Collider with  $L = 2 \cdot 10^{34} \text{ cm}^{-2}\text{s}^{-1}$  @ 126 GeV/beam**  
**Sharp resonance: momentum spread of a few  $\times 10^{-5}$**



Precision energy measurement provided by g-2 effect and residual polarization in muon beams

Han and Liu  
 hep-ph 1210.7803

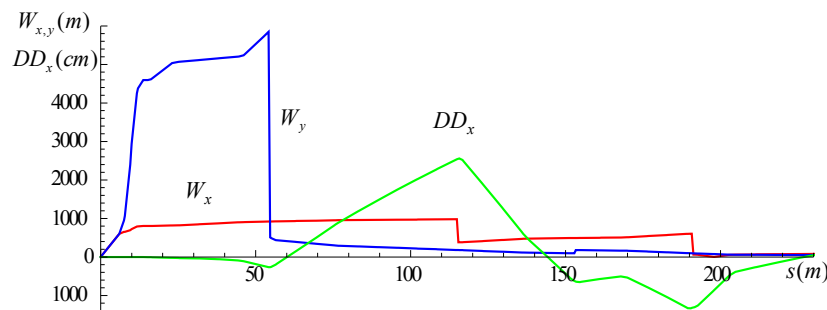
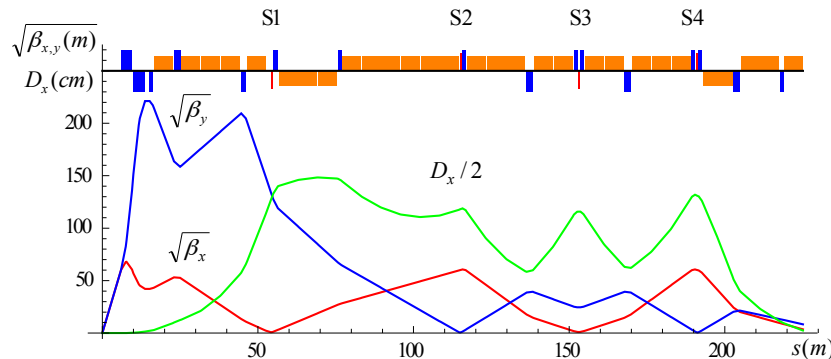


**Major advantage for Physics of a  $\mu^+\mu^-$  Higgs Factory: possibility of direct measurement of the Higgs boson width ( $\Gamma \sim 4 \text{ MeV}$  FWHM expected)**

**Reduced cooling:**  
 $\epsilon_{\perp N} = 0.3\pi \cdot \text{mm} \cdot \text{rad}$ ,  
 $\epsilon_{\parallel N} = 1\pi \cdot \text{mm} \cdot \text{rad}$

# Multi-TeV Collider – 1.5 TeV Baseline

Y. Alexahin



Larger chromatic function ( $W_y$ ) is corrected first with a single sextupole S1,  $W_x$  is corrected with two sextupoles S2, S4 separated by  $180^\circ$  phase advance.

Parameter	Unit	Value
Beam energy	TeV	0.75
Repetition rate	Hz	15
Average luminosity / IP	$10^{34}/\text{cm}^2/\text{s}$	1.1
Number of IPs, $N_{\text{IP}}$	-	2
Circumference, C	km	2.73
$\beta^*$	cm	1 (0.5-2)
Momentum compaction, $\alpha_p$	$10^{-5}$	-1.3
Normalized r.m.s. emittance, $\varepsilon_{\perp N}$	$\pi \cdot \text{mm} \cdot \text{mrad}$	25
Momentum spread, $\sigma_p/p$	%	0.1
Bunch length, $\sigma_s$	cm	1
Number of muons / bunch	$10^{12}$	2
Number of bunches / beam	-	1
Beam-beam parameter / IP, $\xi$	-	0.09
RF voltage at 800 MHz	MV	16

# Muon Accelerator Staging



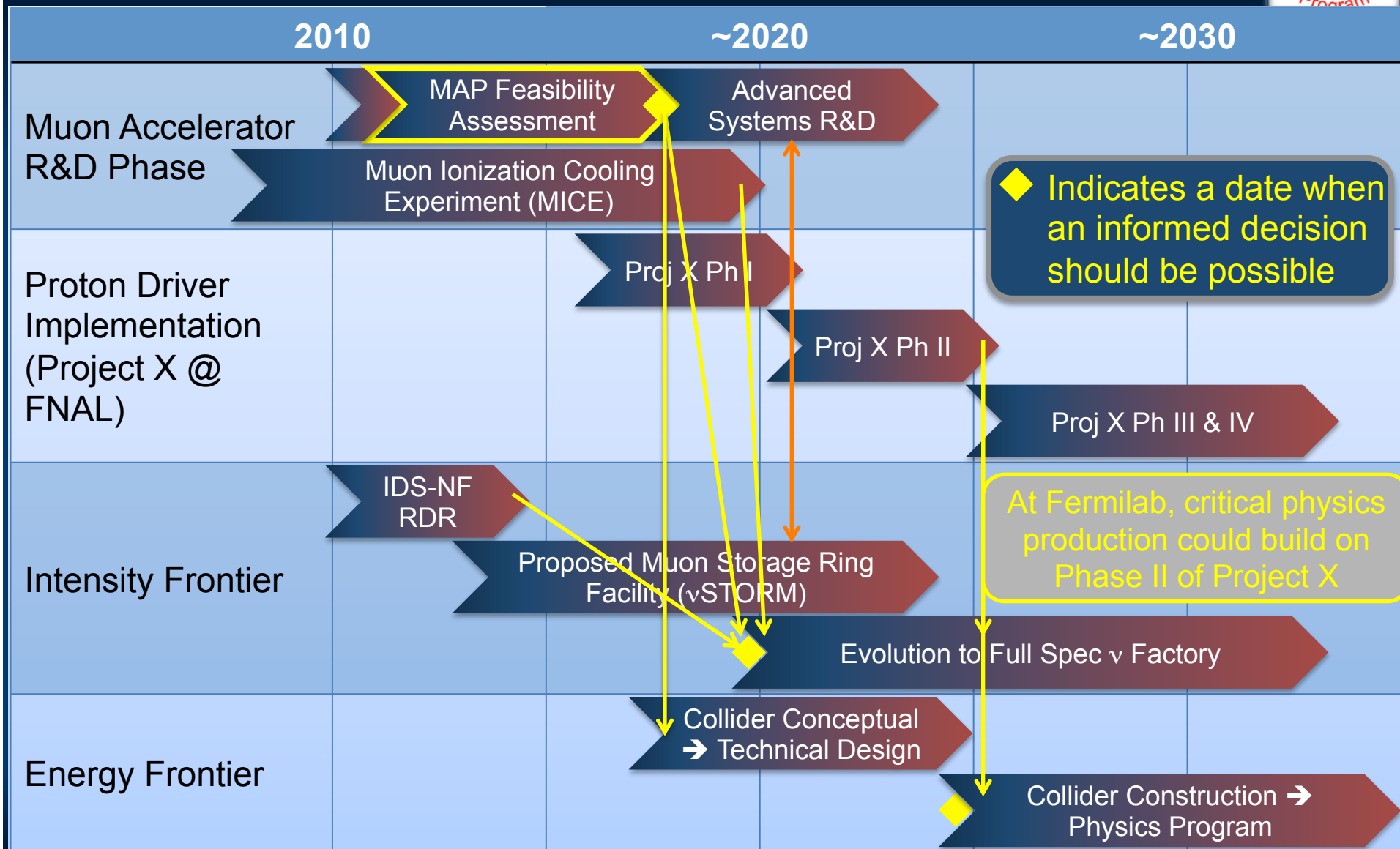
Accelerator	Energy Scale	Performance
<b>Cooling Channel</b>	<b>~200 MeV</b>	<b>Emittance Reduction</b>
<i>MICE</i>	<i>160-240 MeV</i>	<i>10%</i>
<b>Muon Storage Ring</b>	<b>3-4 GeV</b>	<b>Useable <math>\mu</math> decays/yr*</b>
<i><math>\nu</math>STORM</i>	<i>3.8 GeV</i>	<i><math>3 \times 10^{17}</math></i>
<b>Intensity Frontier <math>\nu</math> Factory</b>	<b>4-10 GeV</b>	<b>Useable <math>\mu</math> decays/yr*</b>
<i>FNAL NF Phase I (PX Ph 2)</i>	<i>4-6 GeV</i>	<i><math>9 \times 10^{19}</math></i>
<i>FNAL NF Phase II (PX Ph 2)</i>	<i>4-6 GeV</i>	<i><math>1 \times 10^{21}</math></i>
<i>IDS-NF Design</i>	<i>10 GeV</i>	<i><math>5 \times 10^{20}</math></i>
<b>Higgs Factory</b>	<b>~126 GeV CoM</b>	<b>Higgs/yr</b>
<i>s-Channel <math>\mu</math> Collider</i>	<i>~126 GeV CoM</i>	<i>5,000-40,000</i>
<b>Energy Frontier <math>\mu</math> Collider</b>	<b>&gt; 1 TeV CoM</b>	<b>Avg. Luminosity</b>
<i>Opt. 1</i>	<i>1.5 TeV CoM</i>	<i><math>1.2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>
<i>Opt. 2</i>	<i>3 TeV CoM</i>	<i><math>4.4 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>
<i>Opt. 3</i>	<i>6 TeV CoM</i>	<i><math>12 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}</math></i>

\* Decays of an individual species (ie,  $\mu^+$  or  $\mu^-$ )

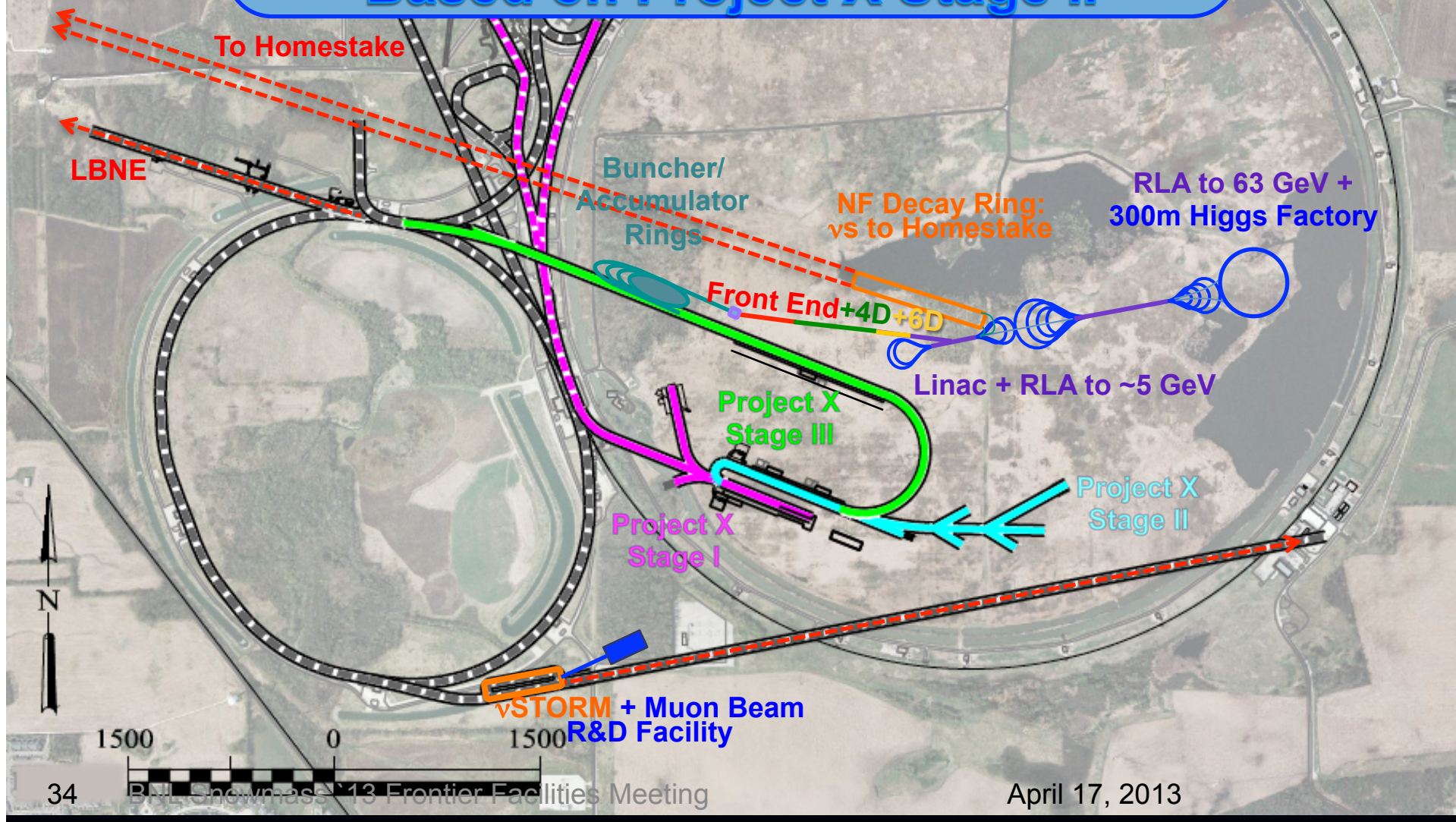


Program Baselines  
And Potential Staging Steps

# The Muon Accelerator Program Timeline



# A Muon Accelerator Facility for Cutting Edge Physics on the Intensity and Energy Frontiers Based on Project X Stage II



# Preliminary Staging Plan Based on Project X Phase 2

## Neutrino Factory Staging (MASS)



System	Parameters	Unit	NuSTORM	L3NF	NF	IDS-NF
Performance	stored $\mu^+$ or $\mu^-$ /year		$8 \times 10^{17}$	$2 \times 10^{20}$	$1.25 \times 10^{21}$	$1 \times 10^{21}$
	$\nu_e$ or $\nu_\mu^*$ to detectors/yr		$3 \times 10^{17}$	$9.4 \times 10^{19}$	$5.6 \times 10^{20}$	$5 \times 10^{20}$
Detector	<b>Far Detector</b>	<b>Type</b>		<b>Mag LAr</b>	<b>Mag LAr</b>	<b>Super-Bind</b>
	Distance from ring	km	1.5	1300	1300	2000
	Mass	kT	1.3	10	30?	100
	magnetic field	T	2	0.5?	0.5?	1-->2 ?
	<b>Near Detector</b>	<b>Type</b>	<b>Liquid Ar</b>	<b>Liquid Ar</b>	<b>Liquid Ar</b>	<b>Liquid Ar</b>
	Distance from ring	m	50	100	100	100
	Mass	kT	0.1	1	2.7	2.7
	magnetic field	T	No	No	No	No
Neutrino Ring	Ring Momentum $P_\mu$	GeV/c	3.8	4	4	10
	Circumference $C$	m	350	1190	1190	1190
	Straight section Length	m	150	470	470	470
	Arc Length	m	25	125	125	125
Acceleration	Initial Momentum	GeV/c	3.8	0.22	0.22	0.22
	single pass Linac	GeV	None	0.9	0.9	0.9
	4.5-pass RLA	GeV	None	4	4	4
	NS-FFAG Ring	GeV	None	None	None	10
	SRF frequency	MHz	None	201	201	201
	Number of cavities		None	50 + 26	50 + 26	50 + 26 + 25
	Total Arc Length	m	50	550	550	550 + 200
Cooling			No	No	4D	4D
Proton Source	Proton Beam Power	MW	0.2	1	3	4
	Proton Beam Energy	GeV	60	3	3	10
	protons/year	$1 \times 10^{21}$	0.2	41	125	25
	Repetition Frequency	Hz	1.25	70	70	50

# MAP Designs for a Muon-Based Higgs Factory and Energy Frontier Collider



**Muon Collider Baseline Parameters**

**Higgs Factory**

**Multi-TeV Baselines**

<i>Parameter</i>	<i>Units</i>	Initial Cooling	Upgraded Cooling / Combiner		
CoM Energy	TeV	0.126	0.126	1.5	3.0
Avg. Luminosity	$10^{34} \text{cm}^{-2} \text{s}^{-1}$	0.0017	0.008	1.25	4.4
Beam Energy Spread	%	0.003	0.004	0.1	0.1
Circumference	km	0.3	0.3	2.5	4.5
No. of IPs		1	1	2	2
Repetition Rate	Hz	30	15	15	12
$\beta^*$	cm	3.3	1.7	1 (0.5-2)	0.5 (0.3-3)
No. muons/bunch	$10^{12}$	2	4	2	2
No. bunches/beam		1	1	1	1
Norm. Trans. Emittance, $\epsilon_{\text{TN}}$	mm-rad	0.4	0.2	0.025	0.025
Norm. Long. Emittance, $\epsilon_{\text{LN}}$	mm-rad	1	1.5	70	70
Bunch Length, $\sigma_s$	cm	5.6	6.3	1	0.5
Beam Size @ IP	$\mu\text{m}$	150	75	6	3
Beam-beam Parameter / IP		0.005	0.02	0.09	0.09
Proton Driver Power	MW	4 <sup>#</sup>	4	4	4

<sup>#</sup> Could begin operation at lower beam power (eg, with Project X Phase 2 beam)

Exquisite Energy Resolution  
Allows Direct Measurement of Higgs Width

Site Radiation mitigation with depth and lattice design:  $\leq 10 \text{ TeV}$

# Concluding Remarks...



- The unique feature of muon accelerators is the ability to provide cutting edge performance on both the Intensity and Energy Frontiers
  - This is well-matched to the direction specified by the P5 panel for Fermilab
  - The possibilities for a staged approach make this particularly appealing in a time of constrained budgets
  - $\nu$ STORM would represent a critical first step in providing a muon-based accelerator complex
- World leading Intensity Frontier performance could be provided with a Neutrino Factory based on Project X Phase II
  - This would also provide the necessary foundation for a return to the Energy Frontier with a muon collider on U.S. soil
- **A Muon Collider Higgs Factory**
  - Would provide exquisite energy resolution to directly measure the width of the Higgs. This capability would be of crucial importance in the MSSM doublet scenario.

***The first collider on the path to a  
multi-TeV Energy Frontier machine?***